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Bromaghim, D., Spanjers, G., Spores, R., et al., "A Proposed On-Orbit Demonstration of an Advanced Pulsed-Plasma Thruster for Small Satellite Applications"
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A Proposed On-Orbit Demonstration of an Advanced Pulsed-Plasma Thruster for Small Satellite Applications

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Abstract - The USAF Research Laboratory's (AFRL) Electric Propulsion Group is developing an Advanced pulsed-plasma thruster (PPT) technology demonstration for small satellites. The initial flight opportunity was on MightySat II.2 - a satellite bus specifically designed to advance AFRL-developed technologies and serve as a risk reduction mission for systems required for TechSat 21. This experiment will demonstrate a high performance PPT, making it a viable thruster for various applications such as orbit raising and initiating and maintaining clusters of small satellites. The experiment will also be the first flight of a new micro-propulsion thruster - a miniaturized version of the PPT, known as the micro-PPT (μ-PPT). The μ-PPT is ideal for very precise attitude control and pointing, formation flying, and for primary propulsion on micro-satellites. A novel on-board diagnostic package will be used to assess the contamination of optical and thermal control surfaces as a result of firing the PPTs. Ground-based observations will also be conducted to assess the on-orbit performance and possible communication impacts of the thruster firings.

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1. INTRODUCTION

A pulsed-plasma thruster (PPT) is an electric propulsion device which traditionally has used two parallel electrodes to ablate and accelerate Teflon™ to produce thrust. A typical thruster schematic is shown in Figure 1. For years, PPTs were used as a simple, effective method for satisfying propulsion requirements, such as attitude control, that can benefit from high Isp while requiring relatively little thrust [1,2]. PPTs have recently undergone development as a means to provide precise attitude control for large satellite formations (100s of m to 1000s of km) such as the NASA interferometer being constructed as a part of the Space Technology 3 Program. These thrusters, however, still suffer from very low efficiencies (<10%) due to a combination of losses from late-time ablation, poor energy coupling into the propellant, and inefficient acceleration. While various research efforts are underway [3,4] to improve PPT efficiency, several novel efforts have stood out that yield significant increases in performance over the historical design shown in Figure 1.

Among these new designs is an Advanced PPT developed by CU Aerospace (CUA) and the University of Illinois at Urbana-Champaign (UIUC) under an Air Force contract, which significantly enhances the thruster performance. The

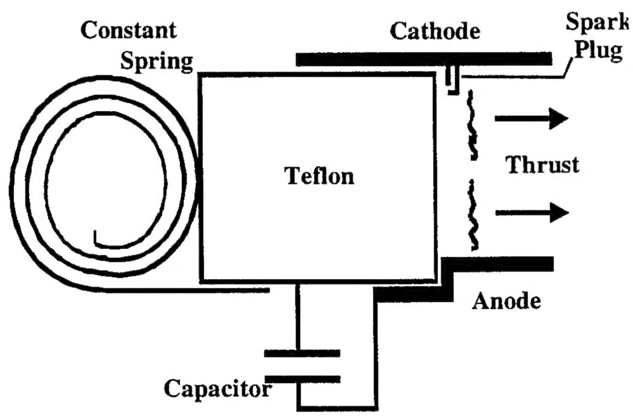

Figure 1 - Generic PPT Schematic

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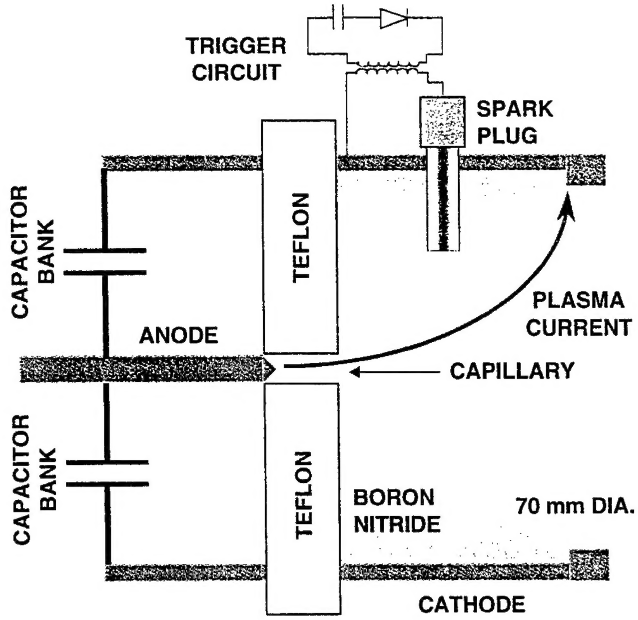

Figure 2 - Advanced PPT Schematic

Advanced PPT, shown in Figure 2, combines a coaxial design (to increase the efficiency of the electromagnetic acceleration) with a capillary discharge chamber to directionally accelerate the large neutral component of the exhaust. Measurements of a laboratory version of this design have shown marked improvements (~4X) in thrust/energy - making this PPT a viable candidate for orbit raising applications on small satellite missions. An engineering model of the thruster is now being tested to verify the performance in a flight-like design.

In a parallel effort, the size of the PPT has been reduced to enable very precise attitude control, or provide primary propulsion on very small (<25 kg) satellites. AFRL has developed a miniaturized version of the PPT, the micro-PPT (μ-PPT), which combines the simplicity of the basic PPT design with very small impulse bits (<25 μ-N-sec). This thruster is detailed further in Section 4 below.

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Small satellites are becoming more attractive as a means to demonstrate new technology rapidly, and as an inexpensive alternative to perform restrictively high-cost missions. These alternative missions, such as the MightySat II and TechSat 21 programs, can greatly benefit from a high performance, easily integratable propulsion system. The TechSat 21 mission, for instance, requires an advanced propulsion system capable of performing the mission requirements while satisfying a set of stringent interface constraints on mass, power, and technical maturity. A trade study was performed by AFRL to determine the optimal propulsion system given the TechSat 21 constraints [5] of mass, power, volume, and technological maturity. The results of this study identified a combination of the Advanced PPT for orbit raising and the μ-PPT for attitude control as the best approach.

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In order to provide a mature, low-risk propulsion system for TechSat 21, AFRL has assembled a team to fabricate, test, and fly a flight version of the Advanced PPT, a μ-PPT, and a suite of contamination sensors on the TechSat 21 satellites. This team leverages off a number of efforts including AFOSR, NASA, and AFRL contracts and includes a wide range of organizations from within the Air Force, NASA, commercial companies, and the university community. This breadth of involvement allows the program to use existing expertise from various areas of propulsion and spacecraft integration in order to deliver the highest quality product. The propulsion package will be delivered in 2001 for integration, system-level testing, and subsequent launch. The diagnostic suite includes a series of radiometers and solar transmission sensors to record any plume contamination effects and the resultant degradation of thermal and optical surfaces. The proposed system is discussed below following a brief description of the TechSat 21 mission.

2. TECHSAT 21 OVERVIEW

Small satellite missions such as the MightySat II and TechSat 21 programs have been detailed in other articles [6,7,8,9]. A brief overview of the two programs is included here to identify the payoffs these types of missions can receive from an advanced propulsion system of this type. MightySat is a dedicated series of space flights to demonstrate AFRL technologies. Since so many of these technologies rely on space demonstrations to validate their readiness, the typical delay (10-15 years) between a development effort and a fielded system seriously detracts from AFRL's ability to support current and future USAF systems. The MightySat program was initiated by the AFRL Space Vehicles Directorate to reduce this transition time by performing these on-orbit demonstrations, and allowing operational users quicker access to the advancements happening throughout AFRL.

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MightySat II.1, the first of these flights, is scheduled to be launched in mid-2000 aboard the second launch of the DoD-developed Orbital/Suborbital Program (OSP). Initially, there was some uncertainty about the launch vehicle which drove the program office to consider a propulsion system to perform the orbit raising. A traditional PPT-based system developed by Primex Aerospace under a NASA contract was initially planned [10], but was later exchanged for a higher thrust system based on a water resistojet (WRT) developed by Surrey Satellite Technologies, LTD [11]. Ultimately, the OSP was selected as the launch vehicle which eliminated the need for a propulsion system, and it was removed from the satellite. Both of these systems have since been fully developed, and will be operated on other satellites (the PPT will be flown on NASA's EO-1 mission [12], and the WRT is operating on UoSat-12 [13,14]).

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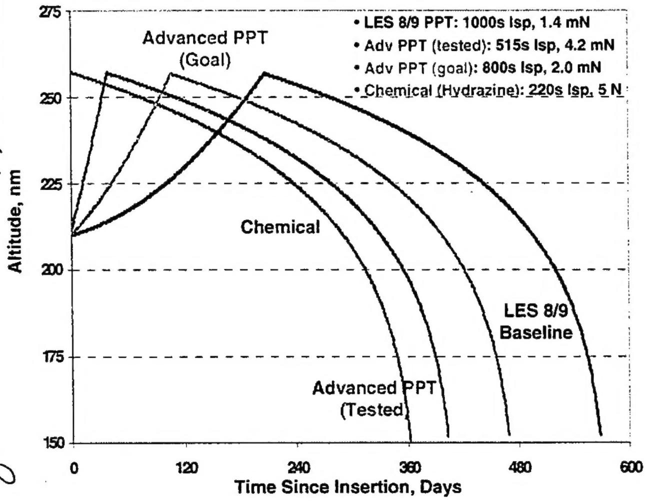

Figure 3 - Resultant Increase in Mission Duration Resulting from Various Propulsion Systems on the MightySat II.2 Spacecraft

The second flight in this series, MightySat II.2, was originally chosen as a precursor to the TechSat 21 mission. As such, the Advanced PPT was selected as the propulsion system to provide the initial orbit raising. Figure 3 illustrates the effect of various propulsion systems on the satellite lifetime. Without a propulsion system, the life is limited to approximately 72 days assuming a spacecraft mass of 180 kg, and an insertion altitude of 390 km. The LES 8/9 design is used as the baseline for the PPT comparison, and a chemical system is shown, even though the disadvantages of such a system (tankage, safety issues, etc.) are not addressed. The two cases for the Advanced PPT are at 100 W input power and are results from the "Tested" performance of a laboratory model, and the "Goal"

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Table 1 - Some Advantages of a Small-Satellite Formation Compared to a Single Satellite for Similar Mission Requirements

Issue	Small-Satellite Formation	Single Satellite
Cost	Low - Multiple copies of a single, simple design	High - Single, complex design
Operational Risk	Low - Failure of one satellite is amortized over constellation	High - Failure of satellite ends capability
Flexibility	High - Formation spreading can be varied for different applications	Medium - Hardware design fixes capability (trade-off with cost)
Capability	High - Size of formation (no. of satellites) is only limit	Medium - Hardware design fixes capability (trade-off with cost)
Developmental Risk	High - Never before demonstrated	Medium - Some development required

of the flight system (driven primarily by PPT dry weight). The Advanced PPT is an ideal system for this small satellite application since it has relatively low power requirements, and fits within the spacecraft structure with relative ease. More specific details on the Advanced PPT are described in Section 3, below.

The TechSat 21 mission is a relatively new system whose main objective is to demonstrate the capability of small satellites (~100 kg) to fly in formation and act as a single entity. Illustrated in Table 1 are some of the advantages a formation of satellites has over a single, monolithic system for a given set of requirements. There are, however, some development risks that must be alleviated, which is the primary objective for TechSat 21 mission. This flight will demonstrate all of the technologies needed for a small satellite constellation with a specific emphasis on demonstrating the cluster's ability to perform ground imaging with a dispersed aperture. The mission will also validate the formation's ability to act as a single entity for commanding and telemetry. The mission consists of three satellites operating in a formation to demonstrate the crosslink capability, command and control algorithms, and the propulsion required to initiate and maintain the cluster.

Recently, the TechSat 21 and MightySat II missions have been consolidated in order to conserve resources. Under this plan, the propulsion system will be optimized for the TechSat 21 flight since the bulk of the design work to-date, and most of what is presented here, has been focused on MightySat II.2. Since there will certainly be changes to the interface requirements assumed here, there will be changes to the system that is ultimately delivered for flight. Nonetheless, the system presented forms the basis of the flight design and enables a significant amount of flexibility for future applications.

3. ADVANCED PPT DESCRIPTION

The Advanced PPT developed by CUA and UIUC under an Air Force contract is a significant advance over the current state-of-the-art in terms of performance and packaging flexibility. This thruster was developed as a result of the work performed at AFRL [15,16] which identified an inherent limit of the PPT efficiency due to loss mechanisms from late-time ablation and propellant inefficiencies. The Advanced PPT incorporates a coaxial geometry to improve the efficiency of the electromagnetic acceleration and uses a capillary chamber to direct the high-pressure gas, produced by the propellant ablation, into useful electrothermal thrust (ref. Figure 2). The Teflon™ is fed into the thrust chamber from the side with constant-force springs and also acts as a sealing surface for the gas in the capillary. A flight prototype of the laboratory version of the thruster, shown in Figure 4, was designed, fabricated, and tested at CUA [4]. The thrust from the Advanced PPT was almost four times higher than the comparable LES-8/9 performance, making

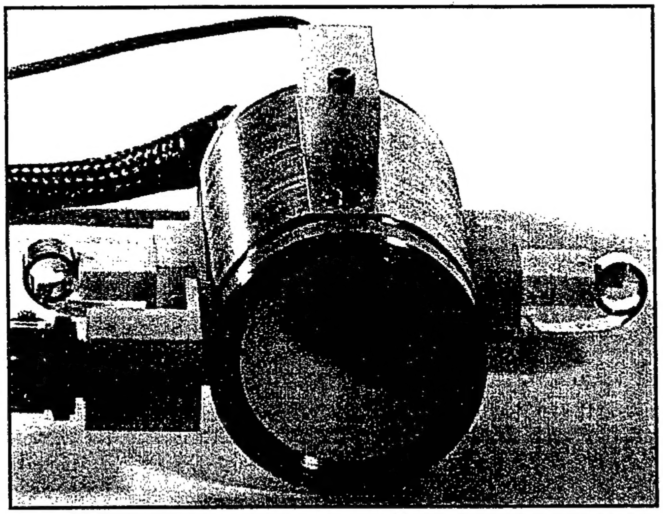

Figure 4 - Laboratory Model of the Advanced PPT

the thruster very attractive for various small satellite missions. The biggest advantage of higher thrust is the ability of the Advanced PPT to escape the higher drag regions of the upper atmosphere faster, ~~and~~ thus increasing the useful satellite life.

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Once the TechSat 21 analyses were complete and the Advanced PPT was identified as the best candidate to perform the orbit raising, the design of a flight version for the MightySat II.2 mission was initiated. The first goal was to identify a design that could attain the required performance and meet a set of interface requirements. The performance requirements were selected based on measurements from the laboratory model. In order to preserve schedule (since the TechSat 21 interface had not been defined), the requirements from MightySat II.1 were used for the interface definition. Efforts are currently underway to optimize the PPT system design for mass, trip time, specific impulse, and thrust level. The preliminary

Table 2 - Summary of the MightySat II.2 Advanced PPT Requirements

Parameter	Requirement
Thrust	~ 2.0 mN
Specific Impulse	~ 800 sec
Mass	~ 6 kg
Power	100 W at 28 Vdc Input
Volume	7 X 7 X 7 inches
Thermal Loading to Spacecraft	< 60 W
Communication Protocol	RS-232
Telemetry Channels	20
Commands	10
EMI Constraints	MIL-STD-461 and MIL-STD-1541
Qualification Level	DoD-HDBK-343, Class D and MIL-STD-1540
Reliability	> 0.9

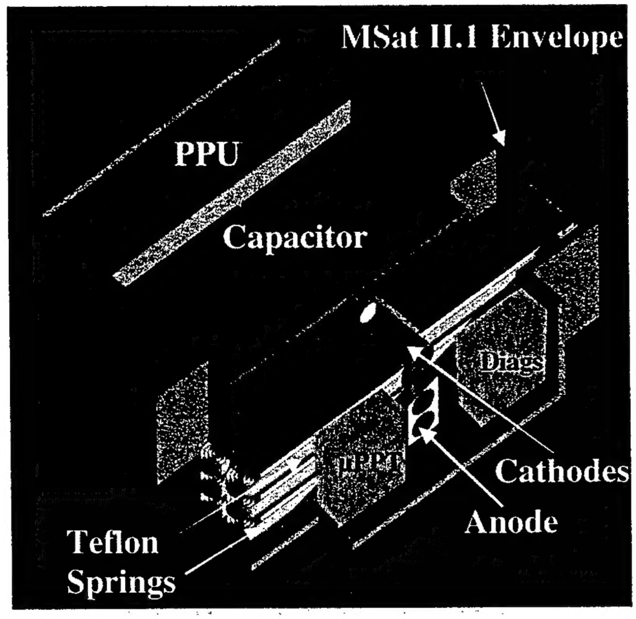

Figure 5 - Preliminary Flight System Design of the Advanced PPT, μ-PPT, and Diagnostics for the MightySat II.2 Application

requirements are summarized in Table 2 and defined the baseline configuration for the Advanced PPT development for MightySat II.2.

Once a preliminary list of requirements was identified, an initial flight design was performed. This preliminary design is shown in Figure 5 and includes a series of stacked thruster modules (four in this case), each of which is a single Advanced PPT. This design allows the side-fed Teflon™ fuel bars to fit within the specified envelope as well as the power processing unit (PPU), a multiplexed discharge initiation circuit, and the capacitor to fit behind the thruster in a neat package. In the preliminary design, the cathodes and spark plugs reside in the rear of the thruster modules, while there is a common anode at the front. The spark plug exciter boxes reside in the front of the thrusters, in the same area identified in the figure for the μ-PPT and the diagnostics. This design allows the Advanced PPT, the μ-PPT, and the diagnostics to fit within a single package - allowing a single interface for the integration, control, and telemetry for the entire system. The μ-PPT and diagnostics development are described in Sections 4 and 5, respectively.

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This design allows significant flexibility for many small satellite missions. Changing the energy level of the capacitor, or the number of thruster modules, or how often they are fired can vary the thrust level. Changing the charge rate of the capacitors and the frequency of the firings can modify the power requirements. Furthermore, for a fixed fuel mass, several thruster modules can be stacked in order to fit into a wide range of envelope configurations.

Once a preliminary design was complete, a prototype of a single thruster module was built and tested at CUA to

Table 3 - Summary of Performance Results from the Advanced PPT Single Module Testing

Parameter	Results
Thrust	4.2 mN
Specific Impulse	515 Seconds at 28 J
Impulse Bit	1400 μN•sec at 28 J
Total no. of Pulses	~10,000
Power	66 - 133 W
Pulse Rate	1-4 Pulses/sec
Peak Temperature	85 °C
Capacitor	34 μF
Total Heat Loss	29% of Input Power

characterize the performance, and identify any design issues. The thruster module was tested with a laboratory power supply and capacitor, diodes and an exciter box from Unison Industries, and the performance was acquired from a validated thrust stand. The single module was operated over a wide range of operating conditions including a successful firing at 133 W - a power level that a single module would never be subjected to on-orbit. As shown in Table 3, the results confirm that there are no technical issues with the design of a single module and demonstrate the performance is within the required range. Other testing completed to date includes the equivalent resistance and the thermal characterization of the capacitor design.

Based on the success of this test, further characterization tests are planned to optimize the thruster's performance for small satellite applications with a more flight-like configuration. The initial testing will continue to use a single thruster module with a prototype PPU, spark plug, and discharge initiation circuit, and will perform a parametric study to optimize the thruster performance. Once these tests are complete, a flight configuration will be selected based on the optimum performance, built up into a prototype multi-module configuration, and tested for performance and life to ensure the thruster can be readily transitioned to a flight configuration. These tests will also

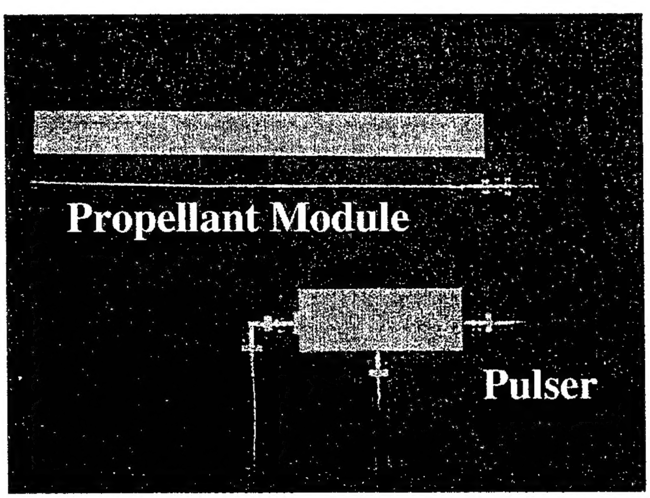

Figure 6 - Laboratory Model of the AFRL μ-PPT

Table 4 - Preliminary Performance and Operating Characteristics of the μ-PPT

Characteristic	Results
Thrust	~ 2-90 μN
Total no. of Pulses	> 500,000
Power	~ 1-20 W at 28 Vdc Input
Mass	< 0.5 kg

be used to verify several of the interface design constraints such as the thermal and electrical requirements. The build-up of the flight hardware will follow with a special emphasis on any interface issues identified in the prototype testing such as electromagnetic interference from the high current discharge, or thermal loads from the thruster and capacitor.

4. μ-PPT Description

The μ-PPT was developed and patented at AFRL [17] and basically consists of a cylindrical Teflon™ propellant module with coaxial copper leads. The thruster, shown in Figure 6, is a simple, low mass device which has operated at AFRL for over 500,000 shots without a failure. The operating characteristics are still being evaluated but a preliminary performance characterization demonstrates the device can be used for a wide variety of applications including very precise pointing, low-mass attitude control, or a near-term solution for primary propulsion on micro-satellites. Table 4 summarizes some of the performance characteristics observed to date.

The modifications required to make the existing design of the laboratory model μ-PPT ready for TechSat 21 are straightforward - primarily packaging and qualification testing. Because there is time available, however, some technology advancements are desirable. The main goal is to remove the transformer since it contributes significantly to the thruster weight and introduces losses into the circuit. This change, already in work, should reduce the mass of the μ-PPT significantly, while improving reliability and making the interface to the thruster as simple as a 28 Vdc input and a single command to trigger the discharge.

The μ-PPT is an enabling technology for the TechSat 21 mission since it allows very fine pointing for the formation while requiring very little power, mass, and volume. The μ-PPT design development performed for the MightySat II.2 flight was focused on validating the thruster and its operation. These objectives were to be accomplished by firing the thruster for approximately one hour after the completion of the orbit raising mission performed by the Advanced PPT. As can be seen in Figure 5, the μ-PPT was placed at the end of the propulsion system envelope and would fire normal to the Advanced PPT thrust vector (vertically in this picture). Firing in the configuration for one hour would cause the satellite to rotate as much as 200 degrees (if not corrected) at an angular velocity of up to 3.5

degrees/minute. The restoring force could be recorded, and the thrust of the μ-PPT derived from combining that measurement with the spacecraft mass and the moment arm to the spacecraft center of gravity.

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5. Diagnostics Description

The diagnostics proposed for the Advanced PPT draw directly from the recent success of the Electric Propulsion Space Experiment (ESEX) [18]. One of the outcomes from the ESEX mission was an effective approach to measure the impact of a thruster firing on satellite operations. This includes several key points: maximize the number of measurements that can be conducted from remote observations (since they have a minimal impact on spacecraft design), perform direct measurements of critical parameters (such as the effect on optical surfaces), and design the diagnostics to be only as complex as the analyses can support (if an effect cannot be delineated from the data, the measurement is only partially useful).

Based on these criteria, a preliminary diagnostics suite was designed that addresses all of the key integration issues including contamination effects on spacecraft and optical surfaces (such as the cover glass on solar arrays), communications tests on the spacecraft command and telemetry links, and an on-orbit measurement of the thruster performance. This suite includes an on-board diagnostics package containing three radiometers with an assortment of spacecraft materials and a bundle of fiber optics with a cover glass. Further measurements will be performed including ground-based communication tests and a series of methods to determine the thruster performance. A preliminary design of the on-board diagnostic package is shown in Figure 7. As shown in Figure 5, this package will be positioned inside of the propulsion system envelope.

Contamination

The contamination resulting from a PPT firing has long been a concern to satellite manufactures because of the potential of the Teflon™ propellant to coat sensitive surfaces. The most successful technique to assess this impact (derived from the ESEX flight experience) is to use a series of radiometers with different spacecraft materials such as thermal paints, radiator materials, or optical coatings. A description of the radiometer operation is detailed elsewhere [19], but the basic technique involves measuring the temperatures at the surface and the base of the sensors and deriving the change in the radiated heat flux as the surface thermal properties are changed by deposited material. The on-orbit radiometer temperatures are compared to the known degradation of the materials under the satellite orbital conditions. Any change from the baseline in the emissivity and absorptance of the materials in the solar spectrum can be used to determine the contamination from the thruster firings. The radiometers place very little burden on the spacecraft from an integration standpoint since they require no power, no commands, only two telemetry channels for each sensor (for two thermistors), and a total mass of less than 0.1 kg.

For the determination of the impact to optical surfaces, the most straightforward technique is to directly measure the change in the solar spectrum absorbed through a cover glass

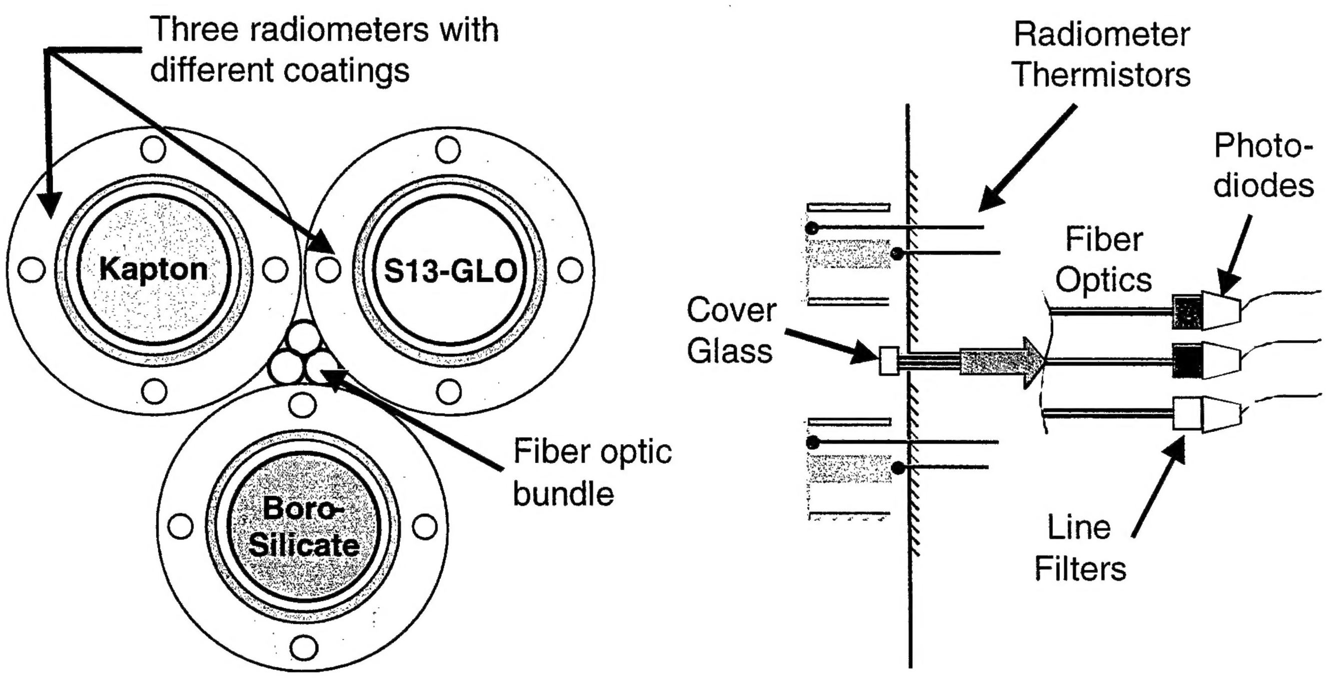

Figure 7 - Preliminary Diagnostic Package Layout Showing the Three Radiometers and the Fiber Optic Bundle

material. The cover glass will be some optical surface material, such as glass or quartz, and will be exposed to the plume of both PPTs. A bundle of fiber optics will direct the solar light onto a series of frequency-sensitive light diodes to measure the change in transmissivity of the surface as the thruster is operated. The frequency bands of the filters and diodes are undetermined, but will be selected based on future applications that can most benefit from the data. These data will then be extrapolated to provide measurements to other spectral regions of interest. Like the radiometers, the fiber optics do not require a significant investment from the host vehicle. There are no commands, only one telemetry channel for each diode voltage, less than 1 W of power, and a total mass of less than 0.5 kg.

Communication Impacts

The communications tests will be accomplished from Camp Park Communications Annex (CPCA) in northern California, using the same technique derived for the ESEX mission [20]. This technique replaces the standard ranging signal with a test pattern that is sent to the satellite, which, in turn directly maps the signal onto the downlink. The received signal is then digitally compared to the original transmission to obtain a quantitative measurement of the bit error rate. The sensitivity of the measurement technique can be adjusted by modifying the transmit power and/or modulation index. This test does not require any special equipment in the spacecraft design. Other, more qualitative tests can also be accomplished such as commanding and telemetry checks to verify each leg of the uplink and downlink, as well as observing the behavior of the other satellite subsystems for anomalous events.

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Performance

Similarly, the performance of the Advanced PPT can be measured through a variety of techniques including the use of satellite ranging data from the Air Force Satellite Control Network (AFSCN), or a GPS receiver (if one is installed on the spacecraft). The AFSCN ranging technique, also developed for the ESEX mission [21], uses standard ranging data to reconstruct the orbits before and after a firing to derive the total ΔV imparted to the spacecraft. Although the Advanced PPT will be operated very differently than the ESEX arcjet, the approach remains similar. In the ESEX case, the firings were relatively short events, followed by 8-10 hours of ranging data to reconstruct the orbit solutions. The Advanced PPT, however, would generally be firing continuously for a significant portion of the orbit (assuming only non-eclipse firings). There are two approaches to satisfy the performance measurement: a series of dedicated performance measurement firings can be accomplished with longer periods of inactivity in-between; or a technique can be derived to account for the spiral transfer. In either case, this measurement has little-to-no effect on the spacecraft design since all of the equipment to perform the ranging is already included on the satellite. The performance measurement of the μ-PPT is discussed in Section 4, above.

6. SUMMARY

New AFLR satellite missions, namely TechSat 21, are focusing on demonstrating that a cluster of small satellites flying in formation reduce the cost and exceed the capabilities of a single, monolithic system with the same mission requirements. The propulsion requirements for the TechSat 21 mission demand the development of an advanced propulsion system that is easily integrated onto resource-limited (i.e. low power, small mass and volume, etc.) small satellites. A high performance propulsion system that meets these stringent mass, power, and volume constraints has been identified in the Advanced PPT, which is now undergoing flight development through the AFRL Electric Propulsion Group. Early testing of this new thruster has demonstrated excellent performance and a flight version could be available as early as 2001. To satisfy the precise pointing requirements of the TechSat 21 mission, a μ-PPT has also been developed by AFRL and is undergoing advanced development to optimize it for the flight requirements. The μ-PPT and the Advanced PPT will both be characterized for on-orbit performance, potential communications impacts, and contamination effects. The contamination measurements will be made with an on-board diagnostics suite developed by AFRL including a set of radiometers and a fiber optic bundle.

7. CONCLUSIONS

For a given set of requirements, a formation of small satellites can clearly out-perform a single satellite for certain missions - especially for large aperature applications such as TechSat 21. The TechSat 21 mission will demonstrate this fact and pave the way for a shift in the way satellite missions are executed. The propulsion requirements for these new missions, however, are aggressive, and can only be met by advanced designs that accommodate flexibility, while maintaining high performance and having relatively little impact on the host vehicle. This mission - to demonstrate the Advanced PPT and the μ-PPT - is a critical step towards validating these propulsion options for small satellite formations. This mission will ensure the thrusters can perform as required, and demonstrate that they have no detrimental effect on the other satellite operations.

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